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SMARTPHONE SENSOR DATA FOR MONITORING TRAM INFRASTRUCTURE - A CASE STUDY OF CLUJ-NAPOCA, ROMANIA

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Abstract

The impressive performance of modern mobile phones stems from their advanced sensors, which are more accessible and cost-effective than traditional industrial solutions. This trend underscores the reliance on mobile technology for various applications. This study examines an Internet of Things (IoT) approach to monitoring segments of the tram network in Cluj-Napoca, Romania, using smartphone sensors to analyse track conditions in real time. By gathering data from accelerometers, gyroscopes, and GPS via a mobile app, vibration patterns were assessed and maintenance hotspots identified. The analysis follows the EN 12299:2024 standard, focusing on indicators of passenger comfort due to vehicle motion. Average comfort, continuous comfort, and discrete event comfort indices were evaluated. Using time-series analysis and geographic mapping, increased vibration levels to specific tram models and track segments were linked. The findings demonstrate that smartphone-based IoT solutions can effectively monitor infrastructure, support predictive maintenance, and enhance operational efficiency in smart city transportation systems.

Keywords: tram, infrastructure monitoring, ride comfort indices, smartphone-based sensing, vehicle-track interaction

1 Introduction

Urban tram systems are crucial for achieving sustainable and efficient transportation. In cities like Cluj-Napoca, where various tram models operate on the same tracks and trams share the road with motor vehicles, the differences in vehicle dynamics must be addressed. These variations can significantly accelerate degradation and complicate maintenance planning, highlighting the need for proactive management strategies. A complete separation of vehicle-, and infrastructure-related effects in comfort-based indicators typically requires detailed information about vehicle characteristics and track geometry. In the absence of such data, this study adopts a relative and spatially oriented analysis approach. By relying on repeated measurements along the same route, the methodology enables comparative evaluations and helps identify localized comfort anomalies that may be linked to variations in infrastructure conditions. The proposed approach highlights that comfort-based indicators can effectively evaluate railway infrastructure conditions, particularly in low-cost, non-intrusive monitoring scenarios where detailed data is lacking. By using smartphone-derived metrics in an urban tram environment, the study aims to demonstrate their potential as preliminary indicators of track-condition variations, thereby aiding maintenance prioritization within a smart-city asset-management framework [9].

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2 State of the art and regulatory framework

The interaction between the track and the vehicle forms a closed loop where track geometry affects vehicle dynamics and motion. In turn, this impacts the track [1, 2, 4, 8, 14, 15]. This dynamic is essential for ride comfort, as outlined in EN 12299:2024. Although the track indirectly influences ride comfort, it remains a key component, along with vehicle characteristics, that determines overall ride comfort performance. Recent studies and professional literature highlight this fact [3-5, 10]. Therefore, it is understandable that recent research has focused on evaluating ride comfort against relevant standards, identifying track irregularities, and establishing links between measured ride comfort and the condition of the vehicle and track. Studies have shown [4, 7, 9-11] that smartphone-based measurements can effectively assess passenger comfort indices, producing results comparable to those of professional systems. Because ride comfort is closely linked to infrastructure geometry, these methods can reliably detect altered track sections and significantly lower the costs of track inspection compared to traditional geometric surveys [2-4, 8, 12, 13]. As noted in numerous studies [2, 4, 6, 12], tram systems experience higher vertical and lateral accelerations than conventional rail due to tight curves, shared traffic areas, and the regular switching between slab and ballasted track sections in urban environments. Common defects such as rail corrugation and track misalignment contribute to these increased dynamic effects. The European Standard EN 12299:2024 - “Railway Applications – Ride Comfort for Passengers – Measurement and Evaluation” provides a consistent framework for objectively assessing passenger comfort solely based on vehicle motion. It describes methods for measuring, processing, and evaluating vehicle accelerations across a range of rail-guided systems, including traditional railways, metro systems, light rail, and tramways.

Although EN 12299:2024 mainly focuses on assessing passenger comfort, its measurement principles are closely linked to vehicle-track interaction. Irregularities in track geometry, defects in rail support conditions, or localized infrastructure degradation can cause increased vehicle accelerations, which are directly reflected in comfort indicators. Therefore, the ride comfort metrics outlined by the standard can also serve as indirect markers of infrastructure condition, particularly when analyzed spatially and over multiple measurement runs. The standard defines several comfort indices to consider when monitoring a specific track section. These include mean comfort, evaluated through standard methods; continuous comfort; and comfort related to discrete events. The assessment of motion quantities – measuring position inside the vehicle - and the track layout, for which these three methods are validated [1], is illustrated in figure 1.

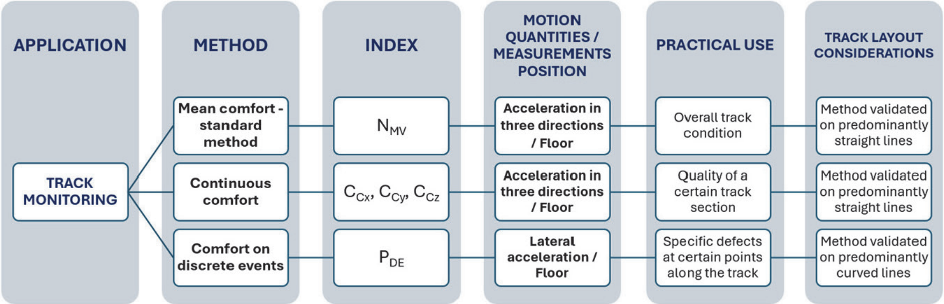


Figure 1 Specification of comfort indices according to EN 12299:2024 for track monitoring [1]

3 Case study description

The Cluj-Napoca tram network consists of a single line running east to west, with multiple overlapping services, covering just under 24 kilometers of track. The network features numerous stops along each route, offering easy access to different parts of the city. Operating speeds are influenced by traffic, track layout, and signal priorities, resulting in varied responses that can be monitored through mobile sensing. The selected measurement sections include representative alignment types, such as straight, curved, and transitional segments. These alignments are important for assessing the spatial variability of comfort indicators and their possible links to underlying infrastructure conditions. Table 1 summarizes the two tram lines included in the case study, which represent the most heavily used sections of the Cluj-Napoca tram network, along with their approximate lengths and number of stops. These are provided as indicative values based on operational data and field observations, which are sufficient for the comparative and spatial analyses performed in this study.

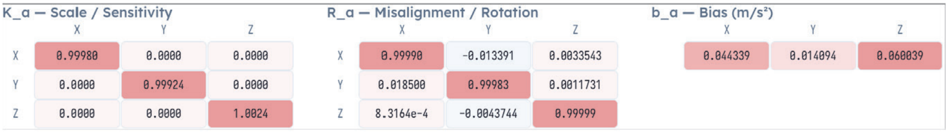
Table 1 Tram lines considered in the study

Tram line	Route description (start station – end station)	Line length [km]	Number of stops
101	BT Arena – Central Train Station	2.8	3 stations outbound 4 stations on the return
102	Liberty West – Unimet North	4.4	8 stations

Two types of tram vehicles operate on the Cluj-Napoca network: Astra Imperio (2020-2021) and Pesa Swing (2012). These vehicles have different dynamic characteristics due to variations in suspension design, mass distribution, wheel–rail interaction behavior, and onboard systems. In this study, data were collected from both vehicle models operating on shared-track sections.

4 Data acquisition and measurement protocol

To ensure repeatability, consistency, and comparability of the collected data, a standardized measurement protocol was developed and employed throughout the measurement campaign. This protocol is designed to align with the principles outlined in EN 12299:2024. It also accounts for the practical constraints of smartphone-based sensing in an operational tram environment. To collect all the data in a consistent format, we used the open-source application phyphox®, because of its support for the full range of available sensors, such as the tri-axial accelerometer, gyroscope, and 1Hz GPS. All measurements were sampled at 100Hz and exported in CSV and Excel formats, preserving double-precision floating-point values. The approach was tested across a selection of devices to cover a wide array of sensor chips. To ensure that the devices were not faulty and were accurate to a certain degree, we applied the calibration methodology as outlined by Ferraris et al. [16] and the open-source implementation by Küderle et al [17]. The calibration process uses gravity to determine three scale factors (K_a), alignment (R_a), and baseline (b_a), as seen in figure 2, for an accelerometer across the 6 faces of the smartphone and its interaction with the onboard sensing unit.



K_a — Scale / Sensitivity

	X	Y	Z
X	0.99980	0.0000	0.0000
Y	0.0000	0.99924	0.0000
Z	0.0000	0.0000	1.0024

R_a — Misalignment / Rotation

	X	Y	Z
X	0.99990	-0.013391	0.0033543
Y	0.018500	0.99983	0.0011731
Z	8.3164e-4	-0.0043744	0.99999

b_a — Bias (m/s²)

X	Y	Z
0.044339	0.014094	0.060039

Figure 2 The results of calibration showcase the profile of a Motorola Moto G72, one of the devices used for measurements

Measurements were taken during regular passenger service on specific tram lines in Cluj-Napoca, without disrupting tram operations or passenger flow. To minimize external influences, measurements were ideally conducted during times of moderate passenger density, avoiding peak hours. Each selected route was travelled multiple times to ensure repeatability and to enable comparative analysis across routes and tram types.

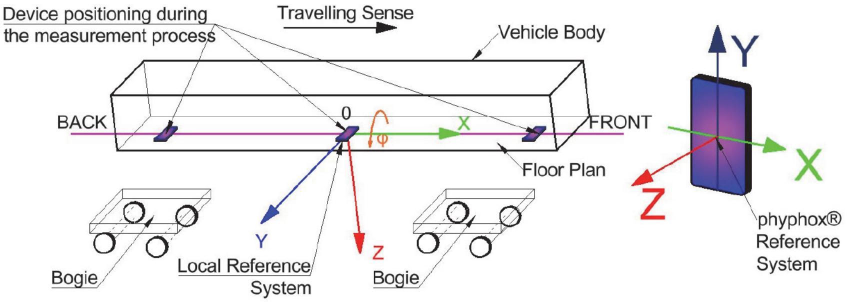


Figure 3 Alignment of the phyphox® reference system with the vehicle body's local reference system, according to EN 12299:2024 [1]

The phones were consistently placed on the tram floor to reduce measurement variability. Throughout all measurements, the devices' orientation was recorded so that the signal axes defined by the phyphox® app could be aligned with the local vehicle reference system specified by EN 12299:2024 during analysis, as shown in figure 3. To meet operational and safety requirements, they were not directly attached to the vehicle structure. The potential effect of this placement on the recorded signals was acknowledged, and future work will explore alternative mounting options to improve measurement consistency. Data logging started before the tram left the designated starting station and ended when it arrived at the predetermined endpoint of the measured section. During the measurement period, the smartphones remained stationary inside the vehicle, and there was no manual interaction with the devices. All measurements were performed using the same sensor settings, placement procedures, and data management protocols, ensuring consistency within the dataset. This approach supports a reliable comparison of ride comfort indicators.

5 Data processing and EN 12299-based Indicators calculation

A key idea of EN 12299:2024 is to derive ride comfort indicators from frequency-weighted acceleration signals (longitudinal, lateral, and vertical), which reflect how the human body perceives vibrations across different frequencies. The standard details a process that first reduces extraneous frequencies outside human sensitivity, then applies frequency-dependent weighting to mimic human perception, moving from emphasizing acceleration at low frequencies to velocity at higher frequencies. To effectively monitor a section of track, it is essential to have data on its geometric parameters. This is because the individual influence of track conditions on comfort indices cannot be evaluated separately [1].

However, even if this data is not available, the indices of continuous comfort, mean comfort, and comfort during discrete events, as defined in EN 12299:2024, can help identify areas where measurements of geometric parameters should be prioritized.

Continuous Comfort ($C_{CE}(t)$) is a time-varying sliding Root Mean Square (RMS)–based comfort indicator derived from frequency-weighted vehicle accelerations, representing the dynamic response of the vehicle–track system along the measured track section. A sliding 5-second time window was used to provide a continuous representation of comfort along the measured track. To evaluate Mean Comfort (NMV), the 95th percentiles of Continuous Comfort values across the three directions were calculated. This assessment can be performed either by combining the values from all three directions into a single mean comfort value or by evaluating the mean comfort value for each direction separately as a partial comfort index. Continuous and mean comfort indices can be used for vehicles traveling on both straight and curved tracks. Passenger Comfort during Discrete Events (P_{DE}) is influenced by lateral acceleration. This comfort index assesses comfort related to specific events, such as local track irregularities, without considering the cumulative effects of multiple events. To analyze the data, the measured signals were processed using a low-pass filter. The vehicle body's lateral acceleration was evaluated with a 2-second averaging window applied to the filtered values, considering the absolute values. From this continuous record, the maximum peak-to-peak lateral acceleration was identified over the 2-second period, producing a new signal referenced to the window center. The P_{DE} comfort index was then derived from these two signals.

6 Results

The data collected from smartphone-based measurements on selected tram lines in Cluj-Napoca focus on variations in comfort-related indicators along the measured track sections. Results are presented in a comparative form, enabling the identification of local differences in comfort indicators and highlighting segments with consistently high response levels. Figures 4 and 5 show the continuous comfort data, calculated through the standard method, along the vehicle's lateral (Y) and vertical (Z) axes at three points: the front, center, and rear of the vehicle.

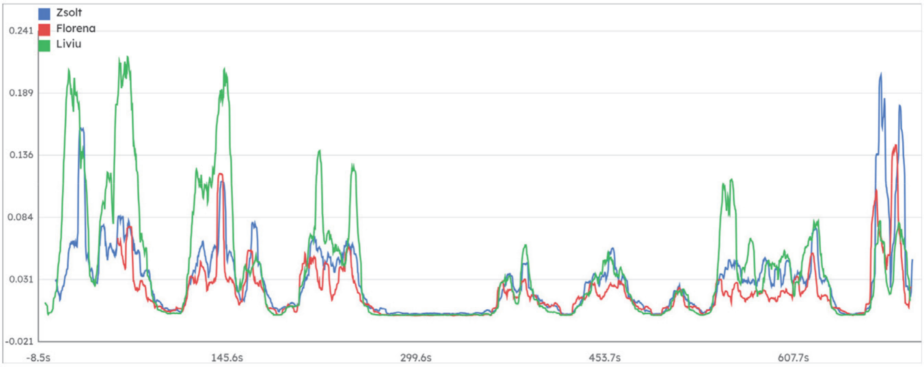


Figure 4 Continuous comfort obtained from measurements by three devices on the BT Arena – Central Train Station route

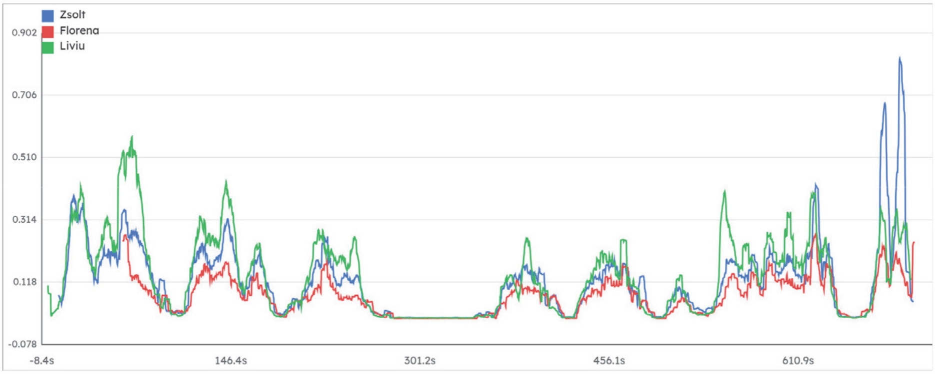


Figure 5 Continuous comfort obtained from measurements taken by three devices along the route from the BT Arena to the Central Train Station

All three devices show strongly correlated temporal patterns across both metrics. The peaks and valleys align closely, indicating that the underlying physical phenomena (track irregularities, braking events, curves) are reliably detected across devices. The systematic offset between devices is less significant than the shared pattern structure since the relative changes remain consistent, although device-specific calibration is needed for absolute comfort values. Most of the observed values on the Y axes stay below 0.2 m/s², indicating a very comfortable ride, while most of the comfort values related to the Z axes above this threshold suggest only a comfortable ride according to the standards set by EN 12299:2024. Importantly, the spikes observed at the end of the measurement are caused by passing over a switch, clarifying the vehicle's localized lateral and vertical movements at that specific location. A graph displaying continuous comfort data along the vehicle's lateral (Y) and vertical (Z) axes, along with discrete comfort event data from measurements of a single device, is shown in figure 6. The data was collected from the second route on Line 102, between Unimet North and Liberty West.

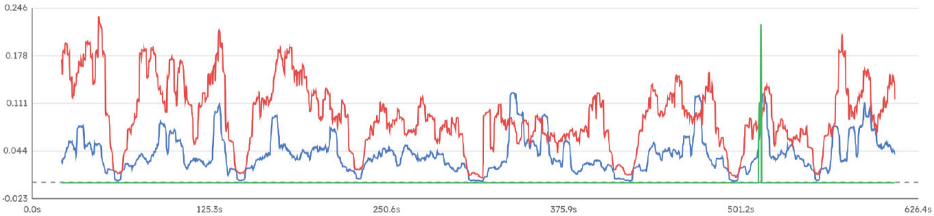


Figure 6 Continuous comfort (in blue) and (in red) along discrete events comfort (in green) measured by one device

The results show that ride quality was generally excellent. Both lateral and vertical comfort values mostly remained below the 0.2 m/s² threshold during the measurement, indicating a "very comfortable" ride according to the standard scale. The vertical comfort displays slightly more variability and peak values than the lateral component, consistent with previous measurements. A mean comfort value was calculated for each trip along a specific route, allowing an overall evaluation of ride comfort. Since continuous comfort may indicate infrastructure issues in certain track sections, for each trip, the highest continuous comfort values along the vehicle's lateral (Y) and vertical (Z) axes, along with their corresponding GPS positions on the track, were extracted and reported in table 2. During both trips, the comfort on discrete events remained at 0 throughout the ride, except at the location 46.794078, 23.600393, where comfort values were recorded as 3.41 and 10.41 for the two trips, respectively.

The data in table 2 show that, unlike in the Y-direction, the continuous comfort values in the Z-direction are significantly higher and more variable. These elevated values suggest that vertical dynamics greatly influence the comfort response in the analyzed section. Importantly, the GPS positions corresponding to the maximum Z-direction values are consistent across both runs and trips, demonstrating strong spatial repeatability. This behavior is typical of track-related features rather than random disturbances caused by the vehicle. Maximum continuous comfort values, along with the average comfort per trip highlighted by color, indicate the same or similar locations of occurrence.

Table 2 Maximum continuous comfort values along the Y and Z axes with corresponding GPS locations

Route Unimet North – Liberty West	Maximum Y Continuous comfort		Maximum Z Continuous comfort		Mean comfort
	Value	**GPS Pos.**	**Value**	**GPS Pos.**	**Value**
Trip 1 (figure 6)	0.126	46.797895 23.611756	0.233	46.796125 23.637782	1.45
	0.124	46.794081 23.60037	0.215	46.795995 23.630166	
	0.121	46.795425 23.602451	0.207	46.790958 23.598763	
Trip 2	0.103	46.794078 23.600393	0.280	46.796180 23.637883	1.61
	0.99	46.790553 23.598348	0.259	46.796077 23.630140	
	0.93	46.795857 23.629147	0.213	46.795613 23.628018	

Figure 7 Showcase of the matched maximal comfort values between Trip 1 and 2

7 Conclusion

The accelerations measured inside the tram reflect the combined response of the vehicle–track system, not just the track condition. In the Cluj-Napoca tram network, it is not possible to directly separate track conditions using track recording vehicle data, as such measurements are not currently performed. Manual geometry measurements do not capture the dynamic interaction between the vehicle and the track. Therefore, the study uses a relative and spatial analysis approach, based on repeated measurements along the same track sections and comparisons between different tram vehicle types. Recurrent vibration peaks that appear at the same locations during multiple runs are interpreted as effects related to the infrastructure. Future improvements could include data fusion with operational parameters and vehicle-specific normalization models to further minimize vehicle-dependent influences.

Even without detailed track-geometry data, the results demonstrate strong spatial consistency in continuous ride-comfort indicators collected from smartphone sensors across multiple trips. The clear temporal connection between these comfort indicators and GPS-referenced peaks confirms that smartphone sensors can identify spatial variations in infrastructure conditions. While these devices reliably record relative trends and local peaks, the absolute comfort ratings have inherent uncertainties. These uncertainties arise from device-specific calibration differences, mounting positions, and variations in sensor hardware. This suggests that smartphone data are better suited as screening tools for detecting anomalies rather than for providing exact absolute measurements. To improve the reliability of the smartphone-based monitoring method, a two-step validation process is recommended. First, the accuracy of the recorded inertial data can be verified by comparing it with measurements from professional sensing equipment. During these tests, the smartphone will be paired with dedicated Motion Recorder Devices (MRDs) equipped with triaxial inertial measurement units (accelerometers, gyroscopes, and magnetometers). Analyzing signals from both systems will help identify sensor bias, differences in frequency response, and potential calibration issues. The second step involves linking the derived comfort indicators to independently measured track geometry parameters. Although such data are not currently available for the Cluj-Napoca tram network, validation could be conducted on railway lines where measurements from track recording vehicles are available. Comfort indices could then be compared with changes in geometric parameters, such as longitudinal level, alignment, cant, gauge, and twist, assessed across standardized track segments. This comparison would help establish relationships between vibration-based indicators and infrastructure condition, thereby increasing confidence in the findings.

Future work will focus on validating the system to support both real-time and long-term monitoring. This will involve adding comfort thresholds specifically designed for tram systems and further refining the analytical dashboard. Improvements will include multi-trip map overlays, enhanced accessibility features, and more effective tools for comparing repeated runs on the same track sections. These findings indicate that smartphone-based monitoring has potential as a future complement to certified instrumentation, offering a scalable and cost-effective way for data-driven tram infrastructure assessment and maintenance planning.

References

[1] CENELEC: EN 12299:2024: Railway applications - Ride comfort for passengers - Measurement and evaluation, European Committee for Standardization

[2] Novillo, G., Rivera, N., Soto-Ocampo, C.R., Mera, J.M.: Analysis of tram comfort using the UNE EN 12299:2010 standard and Sperling method (WZ), WIT Transactions on the Built Environment, 213 (2022), pp. 3–13, DOI: 10.2495/CR220011

[3] Dižo, J., Blatnický, M., Gerlici, J., Melnik, R., Semenov, S., Mikhailov, E., Kostrzewski, M.: Evaluation of ride comfort in a railway passenger car depending on a change of suspension parameters, Sensors, 21 (2021) 8138, DOI: 10.3390/s21238138

[4] Urbaniak, M., Myrcik, J., Juda, M., Mandrysz, J.: The application of mobile devices for measuring accelerations in rail vehicles: Methodology and field research outcomes in tramway transport, Sensors, 25 (2025) 15, 4635, DOI: 10.3390/s25154635

[5] Sventeková, E., Urbancová, Z., Hollá, K.: Assessment of the vulnerability of selected key elements of rail transport, Slovak case study, Applied Sciences, 11 (2021), 6174, DOI: 10.3390/app11136174

[6] Tsunashima, H., Honda, R., Matsumoto, A.: Track condition monitoring based on in-service train vibration data using smartphones, New Research on Railway Engineering and Transport, IntechOpen, 2023., DOI: 10.5772/intechopen.111703

[7] Rodríguez, A., Sañudo, R., Miranda, M., Gómez, A., Benavente, J.: Smartphones and tablets applications in railways, ride comfort and track quality, Transition zones analysis, Measurement, 182 (2021), 109644, DOI: 10.1016/j.measurement.2021.109644

[8] Enhancing railway passenger ride comfort with EN 12299:2024 (CEN-CENELEC), www.cencenelec.eu/news-events/news/2024/eninthespotlight/2024-12-16-railway_en-12299-2024/, 16.12.2024.

[9] Hu, Y., Xu, L., Wang, S., Zhen, G., Tang, Z.: Mobile device-based train ride comfort measuring system, Applied Sciences, 12 (2022), 6904, DOI: 10.3390/app12146904

[10] Stockx, T., Hecht, B.J., Schöning, J.: SubwayPS: Towards enabling smartphone positioning in underground public transportation systems, 22nd ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems, pp. 93–102, Dallas, Texas, 4-7 November 2014., DOI: 10.1145/2666310.2666487

[11] Paixão, A., Fortunato, E., Calçada, R.: Smartphone's sensing capabilities for on-board railway track monitoring: Structural performance and geometrical degradation assessment, Advances in Civil Engineering, 1 (2019), 1729153, DOI: 10.1155/2019/1729153

[12] Silva, P., Ribeiro, D., Pratas, P., Mendes, J., Seabra, E.: Indirect assessment of railway infrastructure anomalies based on passenger comfort criteria, Applied Sciences, 13 (2023), DOI: 10.3390/app13106150

[13] Dižo, J., Blatnický, M., Lovska, A., Ishchuk, V., Ravlyuk, V.: Analysis of ride comfort for passengers in a multiple unit powered by an ecological hydrogen powertrain, IOP Conference Series: Earth and Environmental Science, 1499 (2025), 012071, DOI: 10.1088/1755-1315/1499/1/012071

[14] Dižo, J., Blatnický, M., Lovska, A., Ishchuk, V., Bucko, M.: Analysis of locomotive driver ride comfort, Engineering for Rural Development, 24 (2025), TF020, DOI: 10.22616/ERDev.2025.24.TF020

[15] Stánicz, J., Török, Á.: The role of generations in Rail Vehicle Maintenance, Acta Polytechnica Hungarica, 23 (2026) 1, pp. 165–182

[16] Ferraris, F., Grimaldi, U., Parvis, M.: Three-axis rate gyros and accelerometers, Sensors and Materials, 7 (1995) 5, pp. 311–330

[17] Küderle, A., Roth, N., Richer, R., Eskofier, B.M.: imucal - A Python library to calibrate 6 DOF IMUs, Journal of Open Source Software, 7 (2022) 73, 4338, DOI: 10.21105/joss.04338